U.S. DEPARTMENT OF
ENERGY
Office of Electricity

Demonstration of a 5 MVA Modular Controllable Transformer (MCT) for a Resilient and Controllable Grid

TRAC Program Review

US Department of Energy, Office of Electricity

Presented at Oak Ridge National Laboratory

Oak Ridge, TN

08/13/2019

Prasad Kandula, Research Engineer II
Deepak Divan, Professor
Georgia Institute of Technology

krprasad@gatech.edu
ddivan@gatech.edu

Project Overview

Georgia Tech Center for Distributed Energy

- Objective: Design, build and test a 5 MVA 24 kV/12 kV Modular controllable transformer (MCT) and demonstrate the functionality.
- Budget: $2,293,347 ($1,798,315 + $495,032)
- Period of performance: 06/01/2019 – 05/30/2021
- Project lead and partners
  - Georgia Institute of Technology – Lead
  - Clemson university
  - DeltaStar
  - ORNL
  - Southern Company

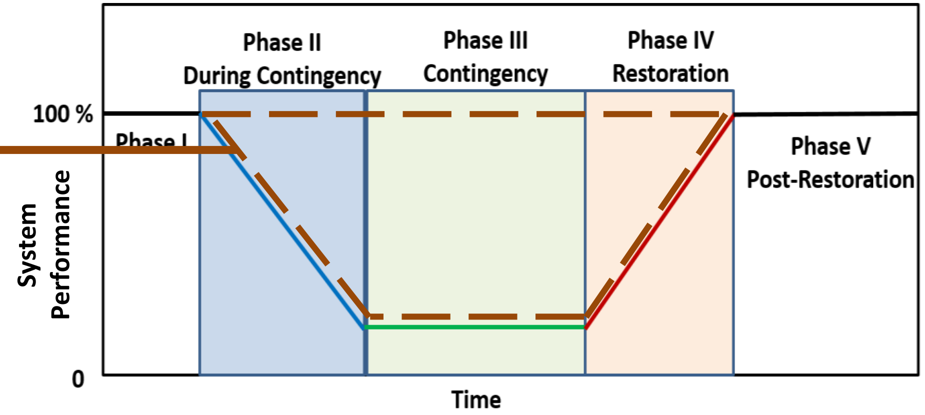
Introduction: Grid Resiliency

- Grid Resiliency is one of the key concerns of modern day grid:
  - The ability of a system to return to an optimal/sub-optimal state following a disturbance.
- The current infrastructure is not equipped to handle High Intensity Low Frequency (HILF) events:
  - Weather-related emergencies (Hurricanes, Lightning Strikes)
  - Physical damage through terrorist attacks
  - Cyber-physical attacks
  - EMP bursts
- Critical Infrastructure sustaining damage:
  - Generators,
  - Transmission Line Networks
  - Substations
  - Large Power Transformers (LPTs)

Today's grid: rapid adoption of DERs, electric vehicles, changing load profiles today's power grid is under increasing stress

Resiliency Metric

Smaller Trapezoid -> More Resilient



MVA-months lost could serve as a measure for resiliency

Large Power Transformers - Problems

Georgia Tech Center for Distributed Energy

- Large Power Transformers (LPTs) are critical pieces of today's electricity infrastructure.
- Failure of a single LPT can disrupt electrical services to 30-100,000 customers.
- Following problems make LPTs extremely vulnerable and very difficult to replace upon failure
  - Aging assets
  - Unique designs
  - Long turn-around times
  - Transportation delays
  - Foreign manufacturing infrastructure
  - Limited flexibility embedded in the grid
- What is the most resilient approach to handling loss of LPT contingency?

Advanced Grid Research
OFFICE OF ELECTRICITY
US DEPARTMENT OF ENERGY

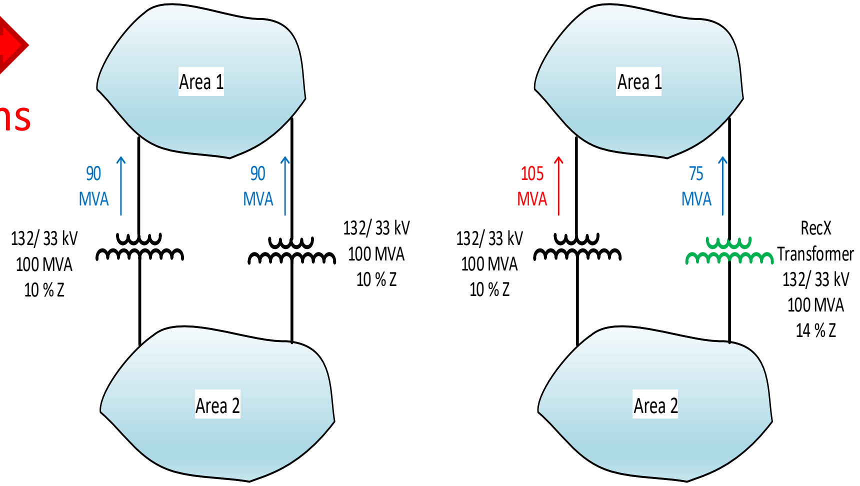
Large Power Transformers - SOA

How does the current infrastructure handle this?

- Mobile Transformers
  - 3-phase units up to 100 MVA and 230 kV delivered fully assembled and prefilled with the transformer oil for fast deployment.
  - For larger MVA, 1-phase modules are used.
- DoE-sponsored RecX transformer
  - Single phase modular transformer
  - Factory to site-installation in 3-6 days instead of the typical 4-6 weeks.
- Spare Transformer Equipment Program (STEP)
- NERC's Spare Equipment Database (SED)

Delta Star Mobile Transformer

Main Problems



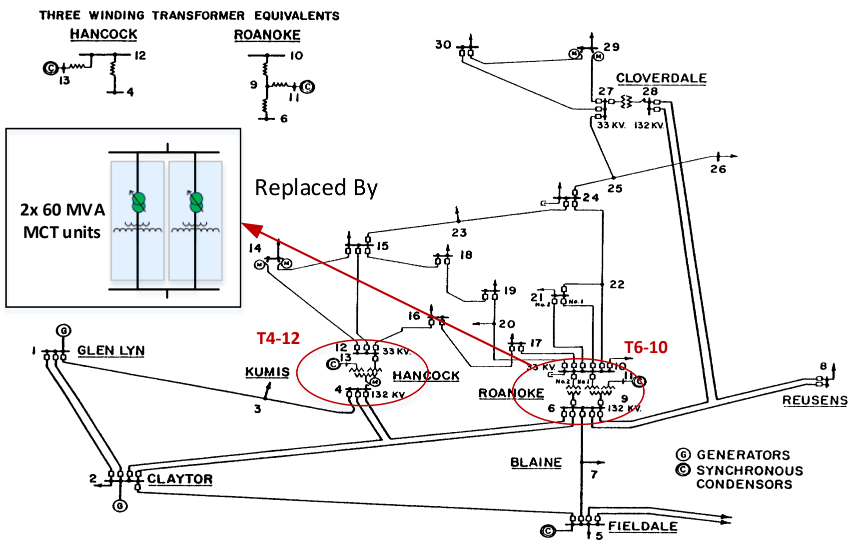
- Mismatched impedance in replacement units causes changes in power flow patterns.
- Higher losses make these only temporary solutions
- Not a fully resilient and reliable approach
- Lack of controllability limits adoption of solutions

Need to stimulate innovative LPT designs that promote greater standardization to increase grid resilience

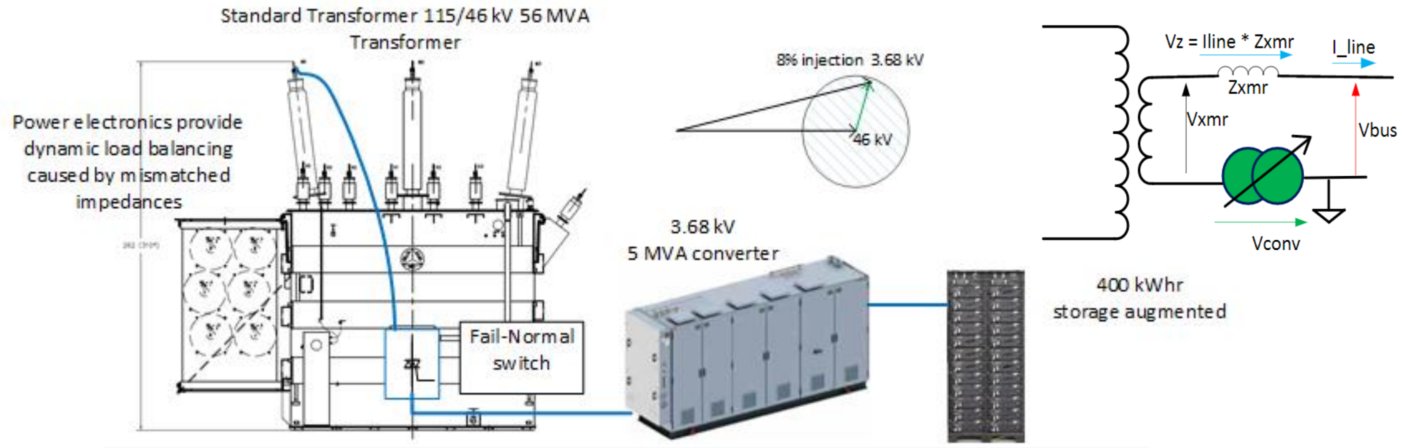
Approach: Modular Controllable (Hybrid) Transformers

Georgia Tech Center for Distributed Energy

Replace LPT with multiple small rated MCTs



MCT: Transformer augmented with a fractionally-rated converter to provide full P/Q/V/I/Z control



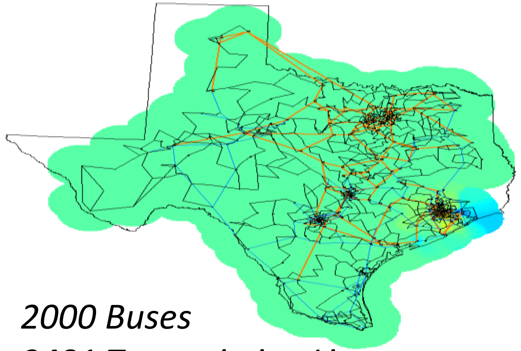
Transformer and fail-normal switch as single unit Converter as a separate unit

Unique Features

- ✓ Standardization - *simplified inventory and build*
- ✓ Modularity - *scalable*
- ✓ Flexibility – *install in a centralized of dispersed way*
- ✓ Mobility – *Faster restoration*
- ✓ Resiliency Improvement
- ✓ Operational control (P/Q/V/I/Z)
- ✓ Fail-Normal – *High reliability*
- ✓ Standard industry designs – *low cost*
- ✓ Fractional-converter rating – *low cost*
- ✓ Simplified converter BIL management

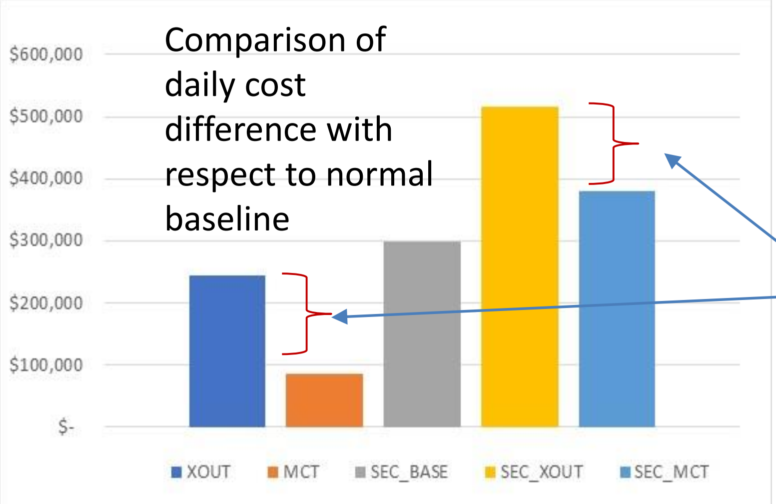
Significance: Case Study

Large-scale Study System



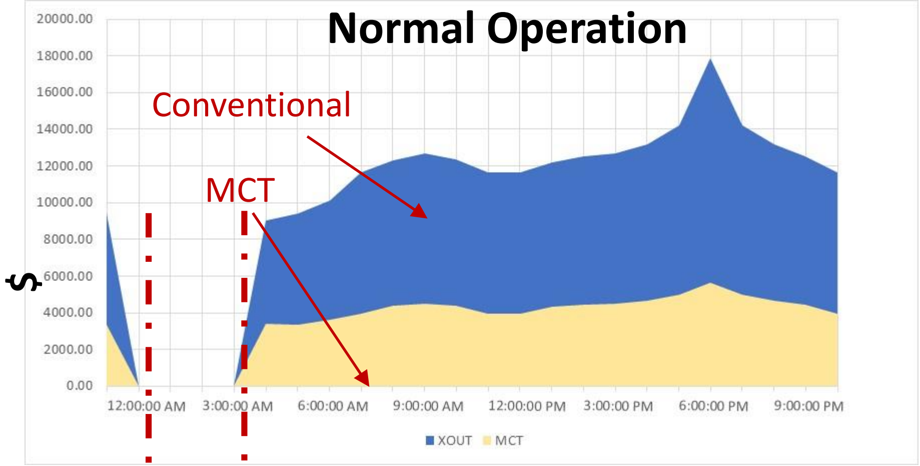
2000 Buses
2481 Transmission Lines
565 LPTs

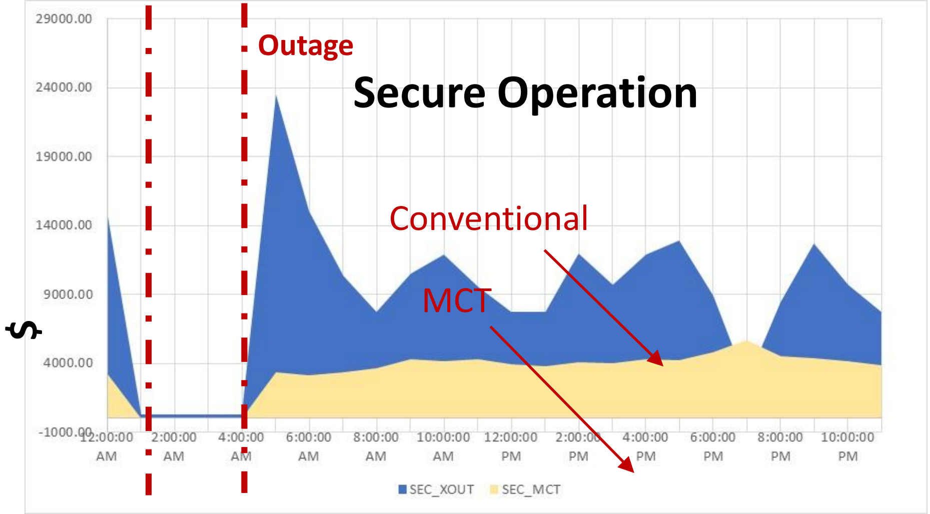
- Simulation includes N-1 contingency analysis and determination of the most severe transformer outages in the Texas system.
- Then outages for a conventional and MCT transformer cases are modeled.
- A 200MVA transformer is considered (replace 200 MVA with three 67 MVA MCTs).



Significant Savings!

The cost difference between conventional and MCT is comparable for both normal and secure contexts.





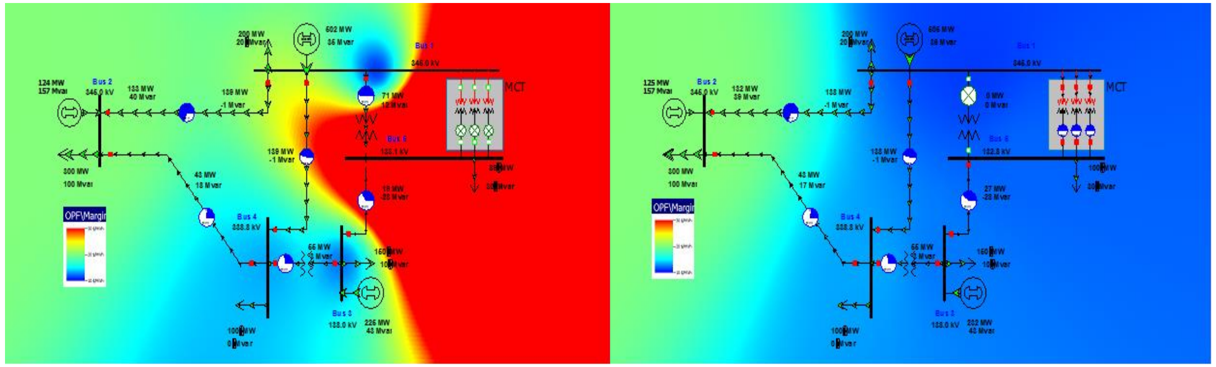
If the disturbance occurs once in the 30-year lifetime of the equipment, the replacement is justified
based exclusively on the improvement in resilience with the MCT as determined by decreased operational cost under secure dispatch – economic impact of power flow controllability not considered

Significance…contd

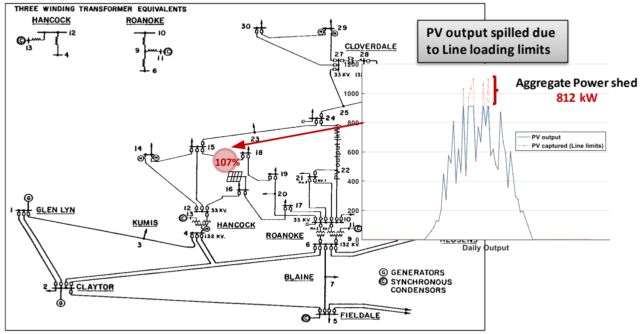
Congestion Management

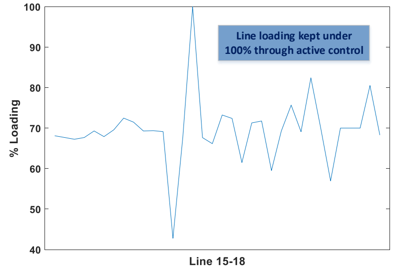
LMP w/o MCT

LMP w/ MCT

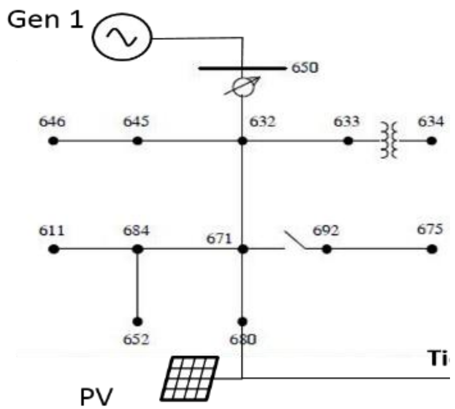


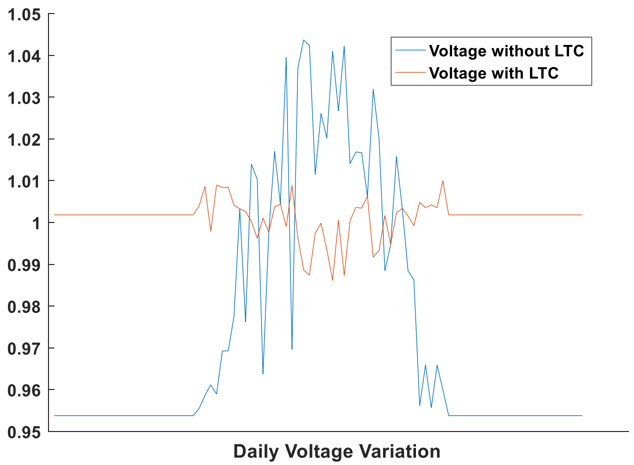
DER Integration Through Power Flow Control



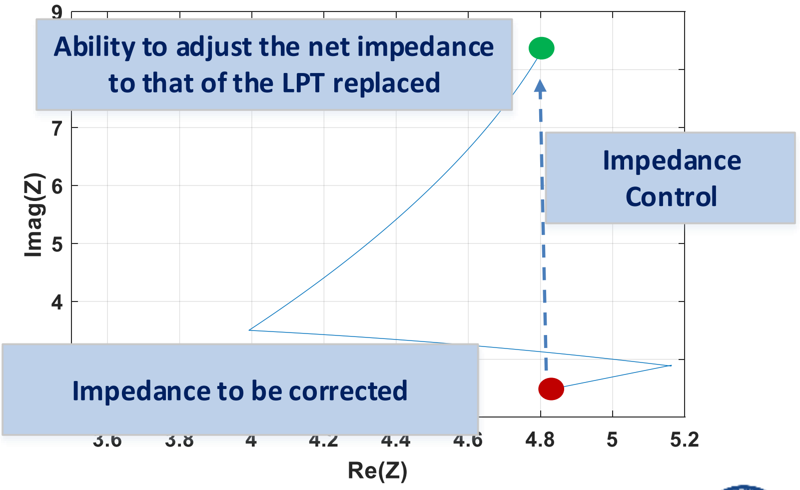


Voltage Control





Variable Impedance

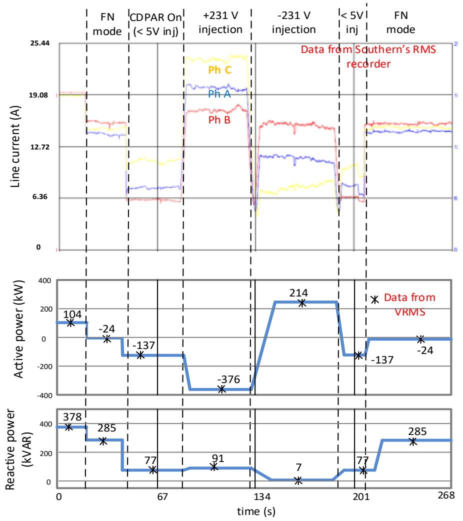


Technology Status

2013-2016/ ARPA-E/G-CDPAR

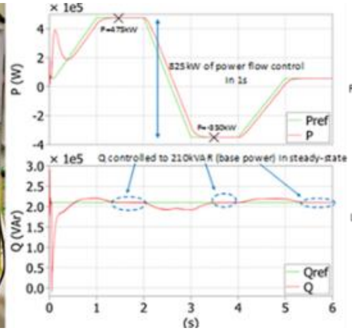
- 1 MVA Xmr w/ 3% voltage injection capability
- 13 kV/1 MW Field Demonstration on a two feeder system

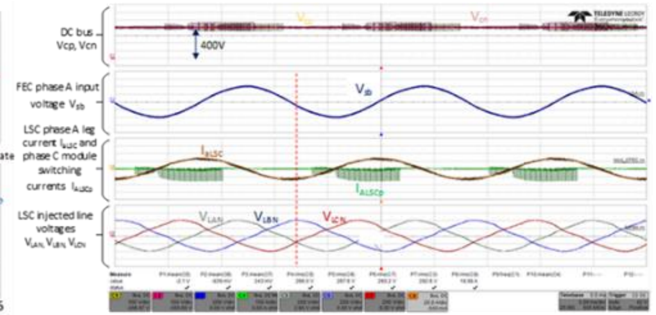
13 kV 1 MW Power Router Field Demo



2017/ARPA-E/G-CNT

- 13 kV 1 MVA Xmr + 5% control 3-level BTB converter
- Demonstrated in lab environment



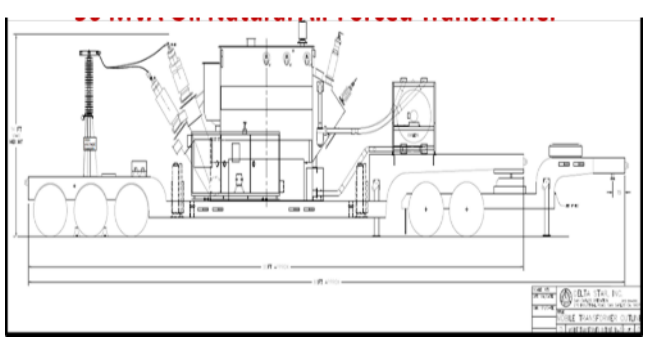


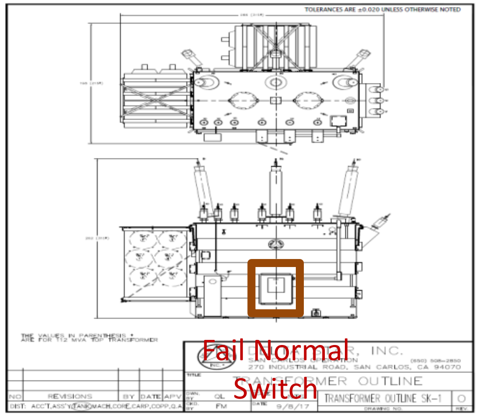
12.47 kV/ 1 MW Back-to-back converter

2017 – 2018 / DOE/ MCT Phase -1

- Replace 200 MVA LPT with multiple small rated Modular Controllable Transformers (MCT) to improve grid resiliency and operational control (P/Q/V/I/Z).
- 139 kV/ 39 kV 56 MVA transformer w/ 8 % voltage control.
- Delta Star designed 56 MVA LPT with following features
  - Integrate fail-normal switch
  - Minimize transportation and commissioning time
  - Shipped with bushings and oil filled

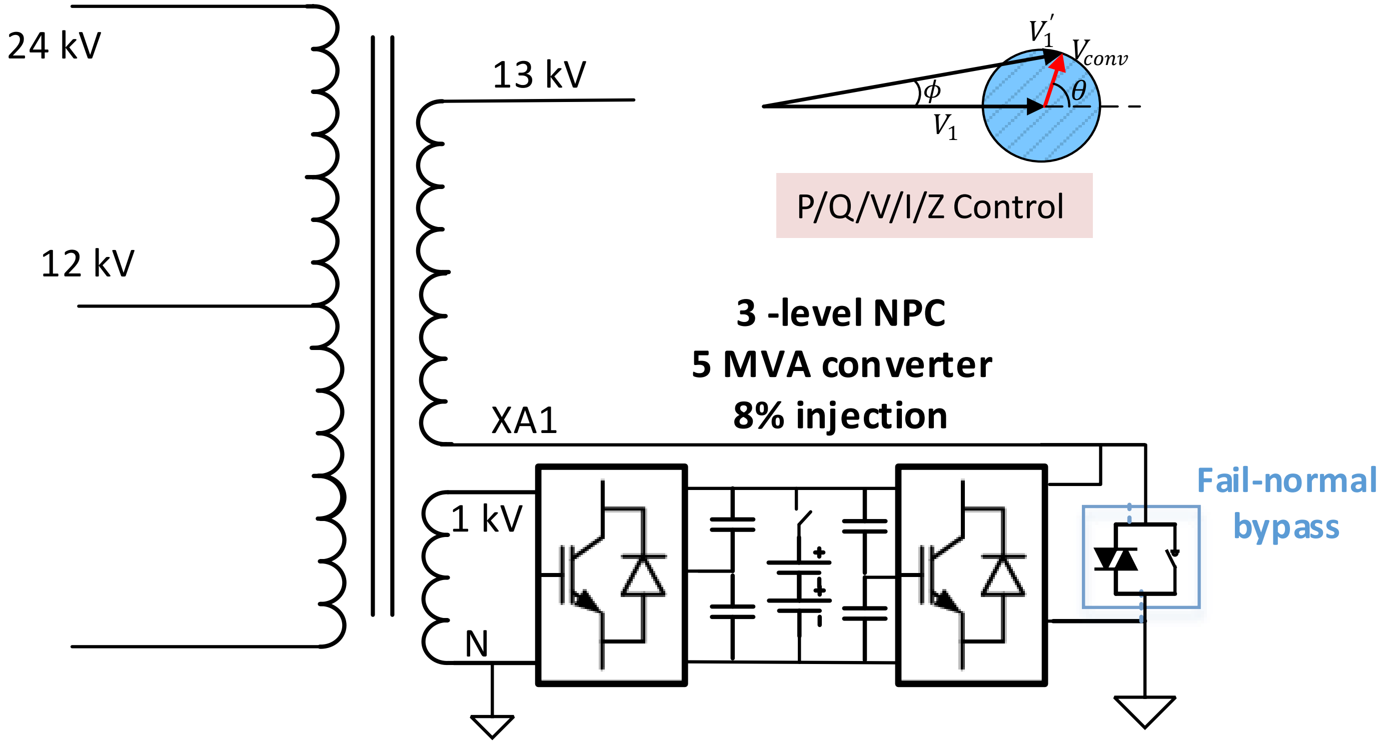
56 MVA Direct Oil Forced Air Transformer





Project Objective

- Design, build and test a 5 MVA 24 kV/12 kV MCT and demonstrate the functionality, which includes modularity, power flow control, interoperability through variable impedance and connection of multiple voltage levels, storage integration, and fail-normal design.
- Assess the impact and penetration level of the proposed MCT and evaluate cost-effectiveness compared to traditional LPTs.



Proposed System Features

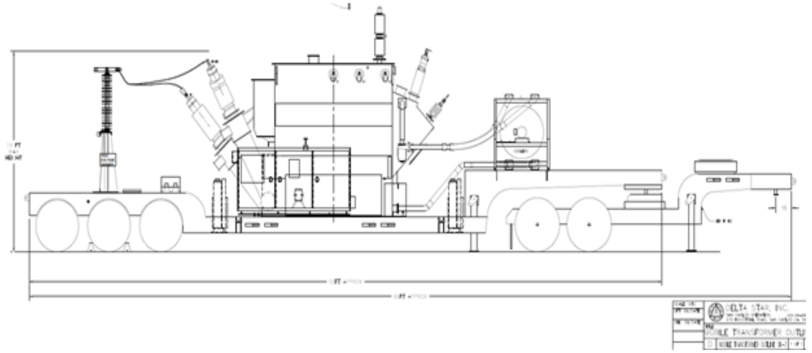
- ✓ Modularity
- ✓ Scalability
- ✓ Backwards compatibility
- ✓ Interoperability
- ✓ Voltage regulation
- ✓ Power flow control
- ✓ Storage integration
- ✓ Fail normal designs
- ✓ Manufacturability
- ✓ Transportability
- ✓ OEM requirements
- ✓ Overload capability
- ✓ Protection

Metric	Units	Goal
Fail Normal Switch – Fault current carrying capability	A	20000 per 20 cycles
Multiple voltages	Number	Dual primary voltages - 24 kV and 12 kV
System efficiency	%	>98.8%
Power flow control	MVA	+/- 0.9 pu
Voltage regulation	%	+/- 8%
Impedance control	%	+/- 3%

10

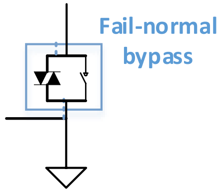
Build Approach

- 5 MVA Transformer
- 24 kV and 13 kV dual primary voltages
- Tertiary taps for converter
- Fail-normal switch integration



3-level Stack from Semikron

Parameter	Value
DC Voltage	1500Vdc
Output current continuous	722Arms
Output voltage	540V-690Vac
Maximum output power	400 kVA
Switching frequency	5kHz
Power factor	-1…0…1
T_{amb}	40°C

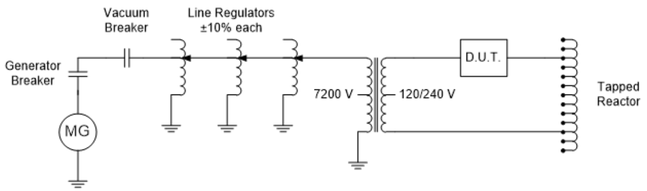


- Normally-closed switch + SCRs
- 20 kA for 20 cycles
- 250 A Nominal current
- 580 V
- Integration with transformer

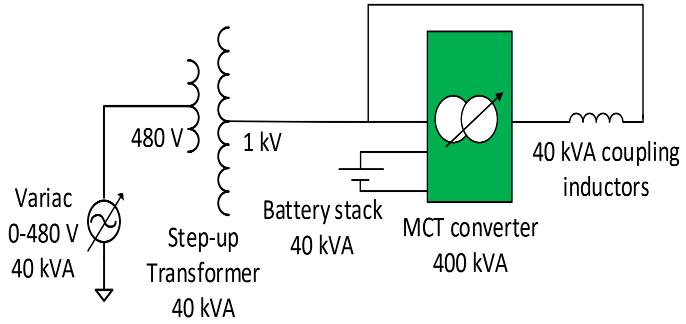
Demonstration Plan

Georgia Tech Center for Distributed Energy

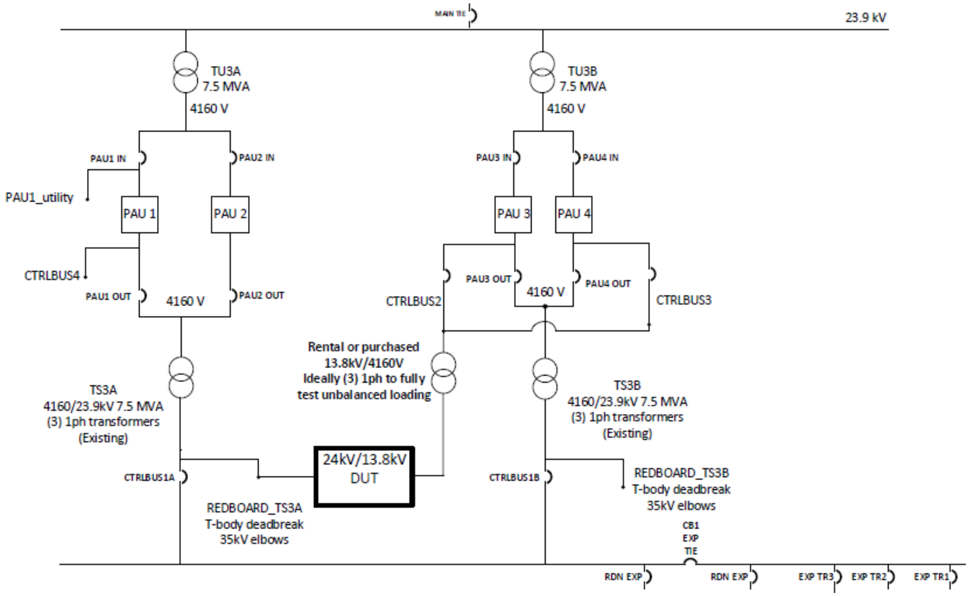
Test fail-normal switch at 20 kA for 20 cycles at NEETRAC, GT facility

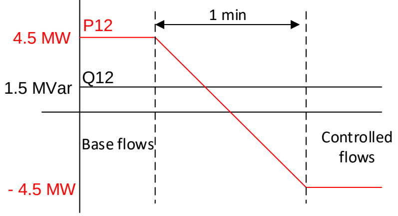


Test 1.0 kV 400 kVA converter at CDE, GT lab



Test at 24 kV Grid Simulator facility, Clemson University





Advanced Grid Research
OFFICE OF ELECTRICITY
US DEPARTMENT OF ENERGY

Project schedule, deliverables, and current status

Georgia Tech Center for Distributed Energy

- Budget: $2,293,347 ($1,798,315 + $495,032)
- Expenditure: Just started

Milestone	Completion Date	Status
Project Management and Planning	6/29/2019	Completed
Product Requirement Document	8/29/2019	In-Progress
Fail-Normal Switch	11/30/2019	
5 MVA Transformer Design and Build	8/30/2020	
400 KVA Converter tested	8/30/2020	
Test Site Preparation	12/30/2020	
Integration and Testing	5/30/2021	
System Analysis	11/30/2020	

Deliverable	Planned completion date
Project Management Plan	6/31/19
Data Management Plan	8/30/19
Design and build of a 24 kV/ 13 kV 5 MVA MCT with +/- 8% voltage injection capability. The 5 MVA unit will be tested at 24 kV test facility to verify the functionality. A detailed report of the test facilities will be generated.	5/30/21
Detailed report for specific use cases and scenarios developed to assess the impact and penetration level of the proposed MCT and evaluate cost-effectiveness compared to traditional LPTs,	2/28/21

Advanced Grid Research
OFFICE OF ELECTRICITY
US DEPARTMENT OF ENERGY

Anticipated challenges and risk mitigation strategies

Risk	Likelihood	Impact	Potential Impact	Mitigation Strategy
Loss of testing facility	Low	High	Scope of project will be reduced or Significant delay in starting demonstration phase in Task 7.0	Build a 13 kV loop testbed at GT to demonstrate certain functionalities of the MCT
Limited test facility capabilities	Low	Low	Functionality demonstrated at a lower power level	
Loss of key individuals	Low	Low	Delay in certain tasks	Backup person is available for every key role
Failure of Converter components during testing	Medium	Low	Delay in demo Task	Redundant/ backup materials will be procured.
Damage of Converter components during shipping	Medium	Low	Delay in demo Task	Use sophisticated freight for safe transportation

Broader Impact

- The results of this project will be widely disseminated through technical conferences and publications.
- The research efforts will also result in graduate students at Georgia Tech and Clemson writing the results of their research in thesis documents, which will also be available.
- Finally, any reports emanating from this project work will also be available for unrestricted viewing.

Thanks

Deepak Divan (ddivan@ece.gatech.edu)
Prasad Kandula (krprasad@gatech.edu)